ON THE

CIRCULATION

OF

THE OCEANS.

BY

CAPTAIN CHARLES WILKES, U.S.N.

PHILADELPHIA:

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THE following Paper on the Circulation of the Oceans, is part of a chapter of Vol. XXIV. of the Exploring Expedition, which is now being published by the Government. I have availed myself of the meeting of the American Association, at Springfield, to present my views on this interesting subject.

CHARLES WILKES.

WASHINGTON CITY, *August*, 1859.

THE

CIRCULATION OF THE OCEANS.

Heretofore, in the Narrative of the Exploring Expedition, (vol. v. chap. 12), I have treated of the flow of the surface currents of the ocean in connection with whaling, not only for the guidance of the practical seaman, but especially for those engaged in the whale fisheries —that great interest of our country for which the expedition was fitted out, and to which its hydrographical labors were more particularly to be devoted.

The subject of the Circulation of the Ocean, and the physical causes which originate and keep it up, have claimed my attention for many years. The facts elicited from the observations made during our explorations, and which other navigators have since confirmed, have led to the adoption of the theory which I shall explain in the sequel.

The circulation of the ocean is apparently one of great complexity, and seems to offer a wide field for research and investigation. I shall endeavor to limit myself to the causes which are known to exist, and adduce such facts and analogies as have a bearing on the many phenomena which have been observed, but remained unexplained, in the movement of the waters.

To effect the circulation of the ocean, it is evident that the forces must be of great power and universal action, to be adequate to produce the vast results we witness. The combined effect of the temperature of the ocean depths and surface, evaporation, the hydrostatical pressure, gravity, and the action of the centrifugal and hydrodynamical forces, we believe are commensurate to this end. While the centrifugal force and evaporation through heat tend to change the form of the fluid mass from its normal state, gravity and the hydrodynamical movements restore it: forces constant and continuous, acting and reacting; forces engendered by the rotation of our planet; forces derived from and governed by the well-known laws of the pressure and movement of fluids, and resulting from the subtile agency of heat

emanating from the earth. These are ever present and always acting on the aqueous parts of our globe, which embrace three-fourths of its surface. All experiments and observations go to show the effects of such action, and we think they afford sufficient data to prove that the circulation of the ocean must result from their combined power.

Before entering upon the circulation of the ocean, we will refer to some interesting facts which experiments have brought to light, relative to the temperature and density of the sea at the surface, and at great depths, which I deem essential to be well understood.

It has been found, by experiment, that a zone of the maximum density of sea-water, as shown by the thermometer, lies between the 55th and 60th parallels of N. and S. latitudes. On this zone the temperature of the sea-water remains constant, and it is found to be invariable to whatever depth the sounding-line penetrates.

At the south, this zone is nearly entire; but from the interference of the land, and the comparatively circumscribed space the waters occupy in the Northern Hemisphere, it varies, within those parallels, somewhat from a direct line.

Assuming, as our guide, the temperature of maximum density of sea-water at a few degrees below that of distilled water,* we are enabled to trace this line in the depths of the ocean, both towards the poles and the equator. This has not yet been done quite as far as practicable, but sufficiently so to establish that it descends rapidly towards the poles, the colder water rising above, forming a *convex* curve; while towards the equator it sinks to the depth of 2000 fathoms, or 12,000 feet, forming a *concave* curve between the two zones, where the warmer water is found above. Beneath this curve an invariable temperature exists, viz., that of the maximum density of sea-water as shown by our thermometers. The diagram on page 7 shows these curves on a section passing through the polar diameter.

By this it will be perceived that the zones of maximum density only touch the surface of our globe on two parallels of latitude, north and south.

It has been long held that the heat of the ocean is derived from the sun; but such an assumption must be erroneous, as it has no facts or analogy to support it. Experiments, of which we have a large number, go far to disprove it, and to show that the heating powers of that luminary can have but little effect upon the ocean.

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* We are aware that the temperature of the maximum density of sea-water depends upon its specific gravity, and that it varies according to the quantity of salt it contains; but with a specific gravity of 1.02800, the temperature of its maximum density may be put down at 36.5.

It is well known that water cannot be heated from the surface downwards, and that it is a very slow conductor of heat in that direction; therefore there is, in effect, a barrier at once raised against the assumption.

The ordinary decrease of the temperature of the ocean, in descending within the tropics, is, for the first 100 fathoms, 6° to 7°, equal to one degree of the thermometer for every 90 feet. In descending on the land, the increase of the temperature is one degree for every 56 or 60 feet of descent.

It must be evident that the heat of the sun's rays cannot penetrate to the depth of the rays of light. In my experiments to ascertain the depth of the ocean to which light reaches, it was found to be in the ratio of the heat of the water. When the sea had the temperature of its maximum density, an object could be seen from 32 to 40 feet; but when the temperature rose above 75° Fahr., it increased to 170 and 200 feet. Between these extremes, the progression of depth is believed to be from 4 to 5 feet for each degree, at which distance the rays of reflected light are visible under the same angle. The experiments indicate that light penetrates the ocean to the depth of 85 fathoms, or 500 feet. If it be true that only one-half of the vertical rays of light reach through the first 20 feet, one-fourth through double this depth, and the $\frac{1}{100000}$th part penetrate to the extreme depths, it must be evident, when the progression of heat from the surface of a fluid downwards is considered, that the heat of the sun cannot penetrate as far as its light, and can only effect the evaporation, and does not tend to raise the temperature, of the fluid, unless in confined spaces or vessels.

When changes occur in the temperature beneath the surface, they can be traced to other causes. The changes of the ocean incident to the seasons are very small, as is shown by the isothermal lines; and proceed more from the effects of radiation and evaporation, than from any heat acquired by the direct rays of the sun. The temperature of the ocean does not vary, in the same locality, night or day, three feet beneath the surface. The highest temperature of the ocean has been estimated to be 6° Fahr. above that of the land.

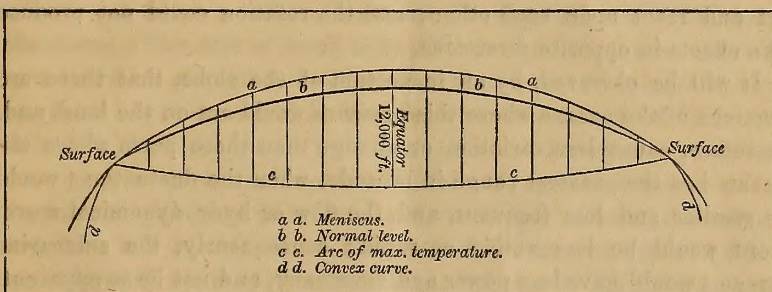
We should not look, therefore, to the sun as the source from whence the ocean derives its heat: it must come from the earth. Experiments have shown us the ratio of the increase of heat in descending towards the centre of the earth, and they also prove that the sea decreases in heat until the curve of maximum density is reached. The average depth of the ocean is computed to be 25,000 feet; and in whatever direction the centre of the earth is approached, the ratio of the increase

of temperature would be the same; and at the above depth it would be found to be, on the solid parts of the earth, about 400° Fahr., or equal to that of red-hot iron.

It is scarcely to be supposed, from our experiences at the surface, that the ocean could come in contact with such a high heat; yet, when the enormous pressure is taken into consideration, it might be so, without any remarkable effects ensuing. We know that the boiling-point of water falls on removing pressure, and rises when it is increased, and that water may be heated to very high temperatures. If such is the case, the heat at the bottom of the ocean might be received as latent heat, be disseminated throughout its mass, and be insensible to our instruments as long as sufficient pressure continued. We believe this point to be the curve of maximum density pointed out on the various parallels before referred to. From this curve upwards the pressure rapidly decreases, and becomes inadequate to confine the latent heat which would be evolved to the surrounding waters, and finally to the atmosphere at the surface.

Although the average depth of the ocean may be as before stated, we are well aware that, in many places where the phenomenon of greatest heat exists, its depth is much less than the curve of maximum density of the latitude, and that the temperature at the bottom might not be over 200° Fahr., and would be more expeditiously disseminated to the waters, and to the atmosphere above. It is well known that there are large submarine streams of a low temperature flowing into immense basins, which, combined with the outflow of the warm water on the surface, would soon reduce them to an equilibrium of temperature with the surrounding seas, if some source of heat did not exist, other than that derived from the sun. As instances, we will cite the Caribbean Sea and the Gulf of Mexico. The assumed depth of these inland seas would assign to the bottom a temperature of from 150° to 200°. Furthermore, if it is a fact that the earth has a higher temperature at the bottom of the ocean than at the surface (which all analogy would go to show), it must follow that this heat is conveyed, after passing into the waters, upwards through the intestinal currents (if the laws of the propagation of heat through fluids remain as they are on the surface), to whatever amount of pressure or compression it may be subjected. As the warmer atoms rise towards the surface, the pressure being gradually removed, its latent heat (if such it is) will be given out, and finally reach the atmosphere above. In no other way could the heat of these seas, including an area of 1,500,000 square miles, be maintained at the temperature of 84° to 88° of Fahr. It is believed that the ocean heat is thus derived and maintained.

We will now recur to the forces which maintain the equilibrium, as well as produce the motion or flow, of both surface and submarine streams. The well-known action of the centrifugal force must tend to draw the lighter particles of fluid of the earth's surface towards the equatorial regions, changing the normal statical level to the form of a *meniscus*, extending north and south of the equator; while the effect of the rotation is also to heap up the fluid on the east side of the continents. This accumulation in height of the ocean lies upon the waters of maximum density as a base, which unites the mass or columns. Experiments have proved that this line is a curve, extending from one zone to the other, the middle of which is 12,000 feet in depth



at the equator. It must result, therefore, that any variation or change of height in any part of the column, would be felt throughout, and the hydrostatical pressure would be changed into a hydrodynamical force, and cause a flow towards the equator, which would be in proportion to the weight and pressure.

The compression of water being as 1 in 20 of its bulk, will operate, as well as its expansion by heat, to increase its volume as it rises from the deep sea, and thus augment the elevation. It will thus be seen that the action and reaction of these forces on each other must be continuous — evaporation, and the centrifugal forces tending to carry off, and destroy the equilibrium; whilst it is restored by the force of gravity, and the hydrodynamical forces engendered. The intestinal currents disseminate the heat derived from the earth, and preserve the temperature of the ocean.

I have made no allusion to the winds, which are often alleged to be the prime cause of the circulation; but I cannot consider that they have any agency, nor can I attribute to them the great and constant action that is necessary to keep up this circulation in the oceans, which we everywhere witness. Doubtless, the winds have their effect

in interrupting these currents, and producing the many anomalies we constantly observe in the surface currents, which tend to retard, change, or increase their flow — raising to a great elevation bodies of water which are confined in bays or rivers; but these are only temporary, and the reaction which gravity brings about soon restores them to a level, or equilibrium.

Neither can I impute to the rotation of the earth the effects we witness in the set and velocity of a stream or current, except so far as the centrifugal force is concerned in elevating the mass. In all the great oceans, we find the streams and currents of great velocities flowing in opposite directions on parallel lines, in the same latitudes, as well as under the equator. The causes must be continuous, and act and react upon each other; and the rotation could not produce like effects in opposite directions.

It will be observed, by an inspection of the globe, that there are portions of the oceans where this pressure would act on the land, and, therefore, cause less variation or change than those parts where the ocean has the greatest range in latitude, when the fluctuations would be smaller and less frequent, and the flow or hydrodynamical movement would be less active or rapid; consequently, the submarine streams would have less power and constancy, and not be so apparent. The ocean, from these zones in the Northern and Southern Hemispheres, is found to set towards the equatorial regions; but the submarine streams, it will be noticed, are found to flow towards and on the eastern side of the great oceans.

Having referred to what I deem essential points, I shall endeavor to explain the action of these forces, which are well known to exist, and enter fully into the consideration of the circulation which they bring about and keep up — noticing all the phenomena they offer.

As heretofore, the streams and currents will be designated as polar and equatorial, from whence they flow, and be classed under four heads, viz. — 1. Submarine streams; 2. Surface streams; 3. Eddy currents; 4. Intestinal currents.

Under the first of these divisions are comprised those great move ments of the waters, from the polar towards the equatorial regions, produced by the hydrodynamical forces. Where the ocean is contiguous, there can be little doubt that the hydrostatical pressure exists throughout the whole extent of our globe. As a large part of the Northern Hemisphere is occupied by land, it will be seen that this pressure must be very unequal; and no hydrodynamical action of any extent can take place, except where there is no land interposed, whereby its action is prevented or deflected. The tendency of the

polar waters towards the equatorial regions, is a well-ascertained fact, proved by the great masses of floating ice and ice-islands, or bergs, which are annually borne to lower latitudes; and by the low temperature of the ocean, traced in a continuous route.

Another fact will serve to prove the existence of these submarine streams. The medusa, which is the appropriate food of the sperm-whale, is generated in the cold waters of the Antarctic seas, and is carried to the low latitudes; and the places where they are deposited are the feeding-grounds of the latter animals. The locomotive powers of the medusa precludes all supposition that they could reach the lower latitudes except through the agency of the polar streams.

There are but four submarine polar streams of which we have any knowledge, viz., one in the Northern Hemisphere, and three in the Southern. The first is found in the North Atlantic Ocean, under the name of the Labrador and Great Northern Polar Stream. It is first perceived off the coast of Labrador, in the latitude of 55° N., longitude 60° W., and appears both as a surface and a submarine stream, occupying a space of the ocean between Europe and America. On reaching the banks of Newfoundland, its surface stream is interrupted and deflected by the waters of the Gulf Stream, which causes it to pass along the coast of Newfoundland, and that of the United States, as far as the capes of Virginia. The great submarine polar stream continues its onward course towards the Azores, Madeira, Canary Islands, and Cape de Verdes, and thence to the equator. Its velocity has been ascertained, by the movement of the icebergs, to be equal to thirty miles in twenty-four hours. Its width continues until it reaches the latitude of 35° N., where it is contracted to nearly one-third its former width, and flows on to the west coast of Africa, surrounding the Cape de Verde Islands, and thence to the equator, where it is found, by its temperature, at the depth of 100 fathoms, to be 200 miles wide. Its whole route is through 50° of latitude, a distance of some 3000 miles. It first inclines to the southeast, and then to the south. Encountering the Cape de Verde Islands, its waters accumulate, or are elevated, and give rise to a surface current, which flows to the southward and eastward, along the shores of Africa, into the Gulf of Biafra.

Of the submarine streams of the Southern Hemisphere, we name: 1st. The Agulhas Stream, which bifurcates on the Cape of Good Hope — the greater part flowing along the west coast of Africa towards the equatorial region, whence it sweeps towards the Bight of Biafra, including the island of Annabon, and thence west towards the equator, where, as before stated, it encounters the Northern Polar Stream.

The Agulhas Stream begins its flow in the 55th parallel of S. latitude, and between 20° and 40° W. longitude. Its onward course is also marked by the ice-islands, or bergs. In its progress to the north, its low temperature is perceived at the surface on the bank from which it derives its name. As in the case of the Gulf Stream, which passes over the Labrador, we here find the Mozambique current overlying and deflecting the Agulhas. There is a difference of some 10° in the temperature of their water. They do not commingle: the warm current from the north sweeps the surface current away to the southwest; but the Agulhas, or Great Submarine South Atlantic Polar Stream, continues its course onwards to the north. Its width at the Cape of Good Hope is not more than 200 miles; but as it sweeps onwards to the equator, it attains, off Cape Palmas, a width of 360 miles. Before it reaches this point, the surface current is again perceived, and has acquired a velocity of from one to three miles an hour, cutting the equator at an acute angle, about the longitude of 25° W., and flows towards the coast of Brazil, merging itself in the Guyana current.

Under the equator, this great southern sub-stream encounters and commingles with the great northern Atlantic submarine stream, which gives rise to numerous rips, boilings, overfalls, bubblings, breakers, and smooth spaces, alternating with rough waters — evincing unmistakeable signs of a conflict by the waters of the submarine streams of the great deep.

A part of the Agulhas Stream flows into the Indian Ocean, and has been traced on the east side of the Mozambique Channel, developing itself along the island of Madagascar. We have no knowledge of its having been discovered in any other locality; and our deep-sea soundings for temperature, as we crossed that ocean on the usual homeward-bound route, failed to show any (unless it was below our soundings) between the Straits of Sunda and the Cape.

The second southern submarine stream sets upon Cape Leeuwin, the southwest cape of Australia, on which it divides — a small part flowing off to the eastward, along the south coast; but the largest part passes on to the north, on the west side of Australia. This submarine stream flows with less velocity, and the surface current is often diverted by the strong winds which prevail at certain seasons of the year. The velocity of the under-current is from fifteen to twenty miles in twenty-four hours, and its extent in latitude is 2000 miles. Owing to the configuration of the Indian Ocean, and its extending but a short distance to the northward of the equator, its hydrostatical pressure remains almost constantly the same, and without those fluc-

tuations which prevail in the ocean that lies in the great valley of the North and South Atlantic, extending from pole to pole. It is asserted that the Red Sea, and probably the Persian Gulf, have a higher level than the Mediterranean. The elevation of the former above the latter is reported at from twenty-four to thirty-six feet; and this is said to be accounted for by the peculiar form of the canal or straits of Babelmandel, at the entrance of the Red Sea! It is much more reasonable to suppose that these waters are maintained at their higher level (if it be true) by the hydrostatical pressure which exists at the equator, acting upon the columns or masses to the north of it.

The outflow from this ocean, by the surface stream on the African coast, is very limited. This, together with the evaporation, is the only discharge we know to occur; consequently, the hydrodynamical movement must be small. The northern part of this sea maintains a higher and more equable temperature, throughout the year, than the Atlantic or Pacific Ocean. Surface currents result from the monsoons, which alternate with those winds.

The width of the Leeuwin submarine stream, abreast the west coast of Australia, does not exceed 150 miles. The first movement of the waters is noticed on the 50th parallel of S. latitude, and 100° E. longitude; and the tendency of the waters of the Antarctic Ocean is from the west towards this locality.*

The third and last great southern submarine polar stream is that which sets on Cape Horn, which divides it into two branches, both of great velocity and extent. The one passing to the east into the South Atlantic is well known—its route is around Staten Land to the east of the Falkland Islands, and from thence it flows northward. This has been recognized by its low temperature, as well as by the conveyance of icebergs to the latitude of 39° S. and longitude 54° W. The velocity of the surface stream, which corresponds with the submarine in direction, has been found to be from 60 to 100 miles in 24 hours; but the submarine stream, as shown by the drift of the icebergs, does not flow beyond 20 miles a day. These, after passing the Falkland Islands, take a more northerly direction. The floating fields of ice spread over a large extent of the South Atlantic, to the eastward of the Falkland Islands, but do not attain so low a latitude as the bergs. The influence of the low temperatures of this stream is perceived as far north as the latitude of 20° S.—showing that it

* As a part of this stream flows on the east side of Australia, towards New Zealand, the low temperature has been found beneath, and the surface current exists to the north of New Zealand—setting towards the northeast, at times, with some velocity.

underlies the current on the coast of Brazil, which sets to the south. This would give it a length of some 2600 miles, and its width off Cape Horn cannot exceed 120 miles; nor is it believed that it spreads as it flows towards the low latitudes in the Southern Atlantic. This polar stream originates, or is first observed, in 55° S. latitude, and 100° W. longitude.

That part of this stream which has been called the Chilian, seems to contract and be deflected as it reaches the coast of South America. About 43° S. latitude, it impinges strongly upon the coast, in the neighborhood of the Chilœan Archipelago. Thence it flows along the coast to the north, and in no part exceeds 100 miles in width. Its velocity is from ½ to 1¼ mile per hour, its flow appears to be regular, and the surface and submarine streams coincide in direction and velocity. Icebergs have sometimes been seen drifting in it, but vast fields of ice are more commonly encountered. The submarine stream is found off the island of San Lorenzo, at about 12° S. latitude, and is here 80 miles wide. It thence flows to the Gallipagos Islands, and invests the whole group. The temperature of the water on the south side is from 10° to 15° below that of the surrounding ocean. The obstructions offered by these islands cause the water to accumulate and be elevated, and to flow off to the west with increased velocity, for a short distance. This great stream pervades the ocean to the distance of 3500 miles, and is continuous; and there can be no doubt of its being urged forward by a constant force. At times the surface current ceases, or is turned aside, and then commences again, probably by the action of the submarine stream, which continues to flow onward, and gradually communicates its motion again to the waters of the surface.

I have thus drawn attention to the four great submarine streams, and their branches, of which we have any knowledge; and have traced them to their furthest limits. At their termini, they all show the violent conflict of the submarine streams before spoken of, except that of the Indian Ocean, which is much less apparent.

There is a large part of the Pacific Ocean where no submarine streams have yet been discovered. I have reference to that portion of the North Pacific lying between the Hawaiian Group and Kurile Islands, and extending to the north of the Aleutian Islands, and beyond 50° N. latitude. There can be no doubt, however, from the configuration of the continents, that the line or curve of temperature of maximum density must exist near this parallel; that the extent of the zone is here reduced to less than 1500 miles in width; and that, though we have no knowledge of the flow of any large submarine stream, yet some of lesser magnitude must exist; for the isothermal

lines of less temperature, in the North Pacific, attain a lower latitude than those of any other ocean. Few experiments to ascertain the deep-sea temperature or submarine flow have been made within this space; but those we have are reliable. They assure us that there is a constant tendency of the water towards the tropical regions, either by the route of the coast of California, or through the straits on the west side of the North Pacific.*

The warm surface stream which flows along the coast of Japan from the equatorial regions to the northeast, is called by the Japanese the Kuvo Sivo. It probably originates on the east side of the Philippine Islands, thence crosses the entrance to the China seas, and flows onwards with a velocity of from twenty to thirty miles a day. The surface current is often interrupted by those caused by the winds, setting at right angles to its course into the China seas. Opposite the straits of Sangar, it makes a curve along the Aleutian Islands to the eastward, and finally disappears on the coasts of Oregon and California.

It has been before remarked, that the normal hydrostatical equilibrium is changed by the centrifugal force raising the fluid mass into the form of a *meniscus*. This meniscus, united with the volume beneath the normal level, and bounded by the curve of density, having the figure of a *crossed lens*, may be considered as constituting a series of columns, as represented in the diagram, whose height diminishes from the equator, north and south, to the zones of maximum density, resting upon and united at the base, and obeying the laws of fluids. Now if, from the effects of evaporation or the outflow of the warm surface currents, the altitude of any of these columns should be changed, a change must necessarily ensue successively in all the columns, and give rise to a transmission of oscillations or waves, followed by a hydrodynamical movement of the ocean waters towards the equatorial regions by the submarine streams beyond the tropics. From the amount of these actions, a correct estimate may be formed of the extent of the others; and where one is perceived, it necessarily leads to the conclusion of the existence of the other. We have strong grounds, therefore, for believing that a submarine polar stream, equal to the evaporation and outflow, must exist in the North Pacific, although none has yet been detected.

The breakers, boilings, rips, bubblings, and counterflows, with

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* A cold current is reported to set with some velocity through the straits of Sangar, and is again met with in the passage between the island of Formosa and the coast of China. This latter, probably, passes beneath the Kuvo Sivo, or Japan current.

overfalls, are also found in the Pacific, showing the conflict of submarine streams, although they are less violent than those we have witnessed in the Atlantic Ocean. The sea lying between the Gallipagos Islands and the coast of South America, is represented by all navigators as the seat of these commotions. They are also found on the west of the Pacific, beyond the Marian Islands, and are met with in the Indian Ocean, near the south point of Madagascar. In all cases, fluctuations of several degrees of temperature are observed.

There are some other features which should claim our attention, as tending to prove the existence of these submarine streams. One is the peculiar form of the continents exposed to them, and the abrasion they have undergone. It will be perceived that all the capes and headlands of the continents exposed to the submarine streams have a peculiar form — a steep and iron-bound coast; while those along which the surface streams flow, are lined by extensive banks and shoals of sand. Where the two are found to meet, the prevalence of the one or the other may be indicated by the description of the bottom. In the one case, they are of mud, or soft; in the other, of sand, or hard. Where they meet the deposits are greater, and the banks or shoals more extensive.

I have before (in the Narrative, vol. ii.) mentioned the oscillation of the ocean, and will now endeavor to account for it. The changes in the normal level which take place through the action of the opposing forces, evaporation and outflow, produce, as before remarked, an oscillation as often as any sudden effect takes place. It will then communicate a wave to each succeeding column, without any progressive motion of the fluid; but if obstacles should intervene, the wave being interrupted, rollers or breakers would occur. These oscillations are found to be more violent at one season than another. The waves come from different directions, passing, according as the disturbance may have originated, to and from the equatorial regions. The oscillations only become visible where obstructions occur.

The rollers take place periodically in some places, and are much greater at those islands which are situated in mid-ocean, Ascension, etc. etc. These appear to take place when the earth is in her aphelion, whilst the former occur when she is in her perihelion; but we require further and more extensive observations to ascertain if this be the fact.

The remarkable oscillations mentioned, in the Narrative, Nov. 7th, 1837, at the Samoan and Hawaiian Groups, were quite different from the rollers. They were found to be coincident with a severe earthquake which happened in Chili at the same time, and to which they

have been ascribed. The velocity of the motion, and the action and reaction which took place, prove that such oscillations of the ocean do occur; and when they are seen, we believe that close observation will detect a difference, and assist in discovering the cause of the phenomena. These oscillations precede the hydrodynamical movement, and point to a change of pressure at the polar or equatorial regions.

There is another phenomenon connected with these waves, which is the elevation of the waters of the Pacific Ocean above their normal level, and that it must have remained so for a period of time. All my observations upon the coral islands have satisfied me that they are undergoing alteration by abrasion from the ocean waves,* and that, at times, many islands have been submerged, so as to have appeared as reefs, and been so described. The wrecks of vessels have been found lying on the tops of islands some twelve feet above high water-mark, and many large trees have been noticed lying from twelve to fifteen feet above the highest tides. The coral rocks show everywhere the effects of abrasion, and large quantities of heavy coral slabs are piled up eight and ten feet above the usual water-marks, on the highest part of the low islands; and distinct marks can be traced on the high islands, some twenty feet above the present high sea level, and these are of comparatively recent occurrence.

On the whole extent of the west coast of North and South America, the phenomenon of rollers takes place periodically. Observations on them have been but little attended to, though the inhabitants of the coast are familiar with them. They are imputed to the tidal wave; but this cannot be the case, for they continue several days, whilst the tidal action endures but for a few hours, and only during the flood. These phenomena do not strictly belong to the circulation; yet they are a part of the system, and show the action and reaction of the fluid mass, and cause some change in the particles of the water. It is, therefore, considered proper to include them.

The well-known Bore is conceived to be another effect of the pressure wave in its onward progress. The oscillations which cause it travel with great velocity, and, coming in contact with the inclined surface of the bottom, the wave, on its deepest side, is no longer balanced by the pressure on the shallowest. Then it breaks, topples

* This is a fact, although not generally admitted; nor is it surprising, when the force of waves has been ascertained by distinguished engineers to be, in the German Ocean, 1½ ton to a square foot; and it is supposed to be double this quantity in the Atlantic. In the vast Pacific and Indian Oceans, it may be considered still greater.

over in a vast breaker, and rushes on with great and overwhelming force (in the Hoogly at the rate of twenty miles an hour), and elevates the water to a full tide.

Now, according to authorities,* the moving force of each of the particles of water is due to the slope of its surface, and also to the hydrodynamical action through the pressure. The former is the cause of the surface, the latter of the submarine streams. It is evident that the action of the first begins at the lowest point where the level or equilibrium is first to be established; and when the lowest particles are removed, they give place to the succeeding ones, until they reach the highest point or level, when the whole acquires a uniform velocity, if its slope is the same. The hydrostatical pressure, undergoing a change by the evaporation and outflow, is restored by the water from the next adjoining column, and this in turn affects its neighbor, and so its action passes on to the zones. By this a submarine stream is established, which becomes constant, although its strength and velocity may vary with the amount of evaporation and outflow. The flow of water through water is retarded by friction against its particles, and by its own viscidity.

We again recur to the system of circulation. It has been shown that a great part of the ocean is elevated, by the centrifugal force, above the normal level; that it assumes the form of a meniscus; that the fluid becomes elevated on the western side of all the oceans, in consequence of its accumulation there by the rotatory movement of the earth from east to west; and that it preserves this elevation, from which the outflow passes off towards less elevated parts lying without the tropics, to the north and south, on the eastern side of the continents. In the North and South Atlantic, the Pacific, and Indian Oceans, it is analogous; but the South Atlantic and Indian Oceans have the simplest form. We find in all a large central space, lying north and south of the equator, which remains comparatively undisturbed, and around which the cold and warm streams circulate. This space maintains almost an equal temperature throughout the year; and as far as our experiments have gone, no submarine stream is known to exist within them. Between the surface and 200 feet, the difference of temperature continues uninterrupted. The boundaries which those spaces occupy, and the area they embrace, are as follows:

* Du Buat and others.

	Latitude.	Longitude.	Area in sq. miles.
North Atlantic........	15° to 35° N.	35° to 65° W.	1,800,000
South "	20 " 30 S.	10 E. " 55 W.	1,950,000
North Pacific........	20 " 33 N.	95 W. " 145 E.	4,680,000
South "	20 " 35 S.	95 W. " 170 W.	3,370,000
Indian Ocean........	18 " 35 S.	55 E. " 100 E.	2,295,000

The North Indian Ocean has no regular circulation: its surface currents depend upon the alternations of the monsoons.

We must not fail to observe that, in the Northern Hemisphere, the ocean circulates from left to right; while in the Southern its movement is from right to left. There are connecting currents between each of these circulations, but they form a very small part of the gyration. The drift currents, produced by the winds, are at times felt over these spaces, but are not to be considered as forming a part of the great and constant circulation. Their flow is but temporary, and in the direction of the wind.

The expanse of water in the North Atlantic, which is strewn over by the *fucus natans*, has been most generally conceived to be a sort of eddy, where other matters, besides the Sargasso weed, are being deposited. This is unquestionably a mistake; for there is little or no driftwood, or other terrestrial products, found within it, and the weed is young and fresh — a fact which has given rise to the opinion that it must be near its place of growth. The tendency of the surface is from this area, which would indicate that it had a higher level. The same remarks will apply with equal truth to the areas which have been pointed out in the other oceans. No doubt, these great revolving streams attract and draw off a portion of the waters of these spaces, to join in the flow as it circulates. At times, driftwood may be carried by an eddy and left within these spaces, and retained there for a long period of time.

The cause which governs the warm surface streams to flow from the equatorial regions towards the poles, is that they occupy a higher level than the colder waters lying without the tropics, and, in obedience to gravity, they flow off to restore the equilibrium.

When a surface stream is perceived, there can be no doubt that its particles are descending an inclined plane to a lower level; and this must continue until the level is restored, either by filling up, or by reduction in height; and should the elevation of the water change to an opposite side, the flow would in like manner return. This we see exemplified in the tides, which we daily witness.

Another cause of the flow of water (to which I have adverted before) is lying above and being in contact with the flow of a sub-

marine stream. So situated, it would necessarily acquire the motion of the fluid on which it rested, and would attain some of its velocity. This effect sometimes causes a flow to begin; and, if unimpeded by any surface current, it would acquire a part of its velocity, and the direction of the submarine stream.

The phenomenon of submarine streams causing an accumulation when obstructed, or encountering a shallow coast, is well known. This elevates the ocean in those places, and a current flows off on either side, with greater velocity than the parent stream previously had. This effect is witnessed in any running brook. The low temperature of the water, when compared with that of the surrounding ocean, satisfies us that it must be caused by a submarine stream. As the distance from these obstructions increases, the velocity decreases, and is finally lost. There are many localities where this effect is perceived; viz. at the Cape de Verde Islands, on the coast of Brazil, near Cape St. Roque, in the North Atlantic, around the Gallipagos Islands in the Pacific, and at all islands and shoals situated or lying in the route of the submarine streams, the temperature of the ocean is found to descend several degrees. This effect of a change of temperature on shoals or banks, has been attributed to radiation of heat, in consequence of the decrease of depth; but it is inadequate to this end. This phenomenon does not appear where submarine streams do not exist.

In consequence of there being a greater flow from the Southern Hemisphere by the three great submarine streams, the line of the greatest heat of the ocean lies to the north of the equator, except on the western side of the Pacific, where the southern submarine streams do not reach, from the interruption of the lands lying to the south; and although we have not found, as yet, any northern submarine stream in the North Pacific, yet it gives another reason to suspect that one exists.

The counter flows I have called eddy currents: they appear to have well-defined limits in all the oceans. The one of greatest extent is that of the Pacific Ocean, which runs between 2° S. and 9° N. latitude, and from 130° E. to 120° W. longitude — a distance of 5500 miles. The eddy in the Atlantic runs between the equator and 5° N. latitude, and from 40° W. to 15° E. longitude. Part of this is known as the Guinea Current. Its western portion is intermittent, but the Guinea Current is constant and has a great velocity, terminating in the Gulf of Biafra, preserving a width of from 180 to 200 miles, and flowing on a parallel, though in an opposite direction, with the Agulhas, or Great South Atlantic Polar Stream, exceeding the

latter in temperature 8° to 10°. Its greatest velocity is from three to three and a half miles an hour. Its temperature in the middle is 84°; on its outer edge, 82°; but next the land from 79° to 80° Fahr.

These eddy currents are not, however, to be considered as originating from the action of the flow of the adjacent waters on each side of them, caused by the trade-winds, but rather from the accumulation of water on the western side of the ocean, from whence they flow, from a higher to a lower level, in obedience to the laws of gravity. The Pacific eddy pursues a course to the east, cutting the meridians and equator at a very small angle. Its width is about 300 miles, and the drift currents caused by the trade-winds, with a variable velocity, run nearly parallel to it. The eastern part of this eddy has been designated, by some hydrographers, as a counter equatorial current.

Of all the surface movements of the ocean, the Gulf Stream has excited most interest; and many have devoted their attention to the investigation of its phenomena. Various causes have been assigned for it, and many hypotheses have been advanced. Some think that the flow of the great rivers which discharge into the Gulf of Mexico and the Caribbean Sea, give rise to it; but a consideration of the supply derived from these sources, soon dissipates the idea of the inadequacy both in volume and velocity. By others the fountain-head has been considered as lying in the Southern Hemisphere, coursing through currents which discharge themselves into the Caribbean Sea and Gulf of Mexico. It may readily be shown that such is not the case.

The elevation of the equatorial seas above the normal level, by the forces already referred to, is adequate to preserve a constant higher level of the waters within, above those without the tropics. The Gulf of Mexico is connected with the Caribbean Sea, and the latter with the Atlantic Ocean, by many deep inlets. These waters are supposed to rest on the same base, and are maintained at the same level by the hydrostatical pressure, and must preserve the same level as the meniscus. There is no constant stream flowing into the Gulf of Mexico from the Caribbean Sea, between the peninsula of Yucatan and island of Cuba; nor is there any current, but the tidal current, setting round its shores. The whole Gulf of Mexico is to be regarded as an immense reservoir, and its waters are maintained at their high level by the hydrostatical pressure of the equatorial seas. The Caribbean Sea may be regarded also as an elongated basin. Both are of great depth; and its waters, like those of the equatorial seas, stand above the normal level. The waters of the Gulf of Mexico are dis-

charged on the east through the channel of the Gulf Stream, at the straits of Bimini. They also escape by a smaller current flowing to the east on the south side of Cuba. The pass over the ledge of Bimini, then, is the spout or outflow from this great reservoir—which has been called the Gulf Stream, and its flow is great—under the law that the pressure outward is equal to the weight of a column whose base is the whole surface, and whose altitude is equal to the depth of its centre of gravity below the surface.

From recent investigations by the officers engaged on the Coast Survey duty, it has been ascertained that in the outlet of the Gulf of Mexico, the depth on a section at the Bimini Straits is but 370 fathoms. There it is thirty-six miles wide. The outflow passes off through this section. The difference in the level of the waters lying to the north, and those of the Gulf of Mexico, permits it to do so, and the difference in both will represent the velocity of the stream. At times, this is much more rapid; and, again, the current has been known to cease or to set into the Gulf. The peculiar and sharp turn to the north taken by this stream, may be occasioned by its meeting with resistance from the banks and shallow water, which, by the facts before alluded to, may be elevated as high as the waters of the Gulf. Its pressure would then act to the northward, and cause it to be turned towards the coast of the United States, which it follows with a decreasing velocity, spreading its waters over a wide area of the North Atlantic, to the north of the space where no current exists; and only ceases to flow when the level is restored.

The Caribbean Sea maintaining the same level as the Gulf oi Mexico, from the same causes, this sea has also a very extensive current on its south side, from the peninsula of Yucatan along the coast of Honduras and Columbia, through a distance of over 700 miles. It has likewise frequent outflows through its outlets to the north. Observations prove that its waters flow, at times, with velocity to the eastward, even against the prevailing winds. It will, therefore, be seen that the equatorial stream does not flow through this sea, but is lost (as I have before remarked) in its conflict with the great northern stream. There is, however, a very strong current known to set from Cape St. Roque to the west, under the name of the Guyana current; but this is imputed to the elevation, from the accumulation of the waters by the South Atlantic submarine stream, on the shoal coast of Brazil. The velocity of this current is very variable, though, when greatest, it equals the velocity of the Gulf Stream; but its course is a short one, and it rapidly decreases, and ceases to flow.

The Gulf Stream offers the best illustration of a warm equatorial

surface stream. From what has been said, it must be governed by the same laws which control the flow of liquids.

Some anomalies, however, connected with the temperature of this stream, and which are recorded in the reports of the Coast Survey, must be referred to. By the observations on the section of this stream across the Straits of Bimini, where it was found that the greatest depth was 370 fathoms, the temperature at that depth was but 34° Fahr., while that of the surface was 84° Fahr. Further to the north we have other sections crossing this stream. The observations are presented in the following table:*

	Surface.	Bottom.	Depth Fath.
In the Straits of Bimini	84°	34°	370
Off Cape Florida	83	49	500
Off St. Augustine	82½	60	510
60 miles to the north of St. Augustine	82	59	540
123 miles further to the North	81½	54	540

It will be observed, by the above record, that the temperature has increased, above that at Bimini, but below the depth of that section, to the distance of 420 miles to the north, 21½° of Fahr., and this extends over an area of more than 8000 square miles, and exceeding it 900 feet in depth; while the surface has expanded itself fully forty miles in width. Now, it cannot be supposed that this vast volume of heated water, existing below the depth of the Straits of Bimini, could have been derived from the Gulf of Mexico, or that it has passed over this ledge. If these results of the Coast Survey are to be depended upon, it does prove that the heat which raised this vast volume of water so many degrees, could not have originated from the equatorial regions, and must have acquired its heat after it had passed the barrier where the temperature of the water was found to be only 34° Fahr. at a less depth.

The temperature of the waters of the Gulf of Mexico have been ascertained to be about 44° Fahr. at the depth of 1000 fathoms. From this depth the water may rise and flow out over colder strata; but we are constrained to doubt that, after passing that strait, where so low a temperature is said to be found, it should again, contrary to the laws of the specific gravity of fluids, descend to occupy a lower level, with a temperature so much higher. The same records, as before observed, give evidence that the warm water of the Gulf Stream, in its progress to the north, spreads to a great width. They also assert that the cold temperature of the depth on the Bimini section, is a

* See Coast Survey papers for 1855, p. 55.

proof that a colder stratum of water underlies the Gulf Stream. Such does not appear to be the case, from the facts of the record, which offer the most satisfactory proof that can be adduced, that the heat must have emanated from the earth by the intestinal currents. All analogy would forbid us to assign its origin to the Gulf Stream, or to suppose that its waters, which are specifically lighter, could flow under those that are denser and colder.

The separation of the cold and warm-water streams are always well defined, and in many localities more so than the Gulf Stream. I refer to the equatorial stream and the Guinea current. The latter I have classed under the eddy currents. These run side by side, in opposite directions, for upwards of 1000 miles, and preserve throughout a well-defined margin, without commingling. This is probably owing to the intestinal currents, which, ascending and descending, serve to prevent it. Experiments, on a small scale, exhibit this effect, and show distinctly that the movements of the ascending and descending currents are well defined, and have the same well-marked line of separation.

The excessive heat to which the bottom of the ocean is subjected, must act upon the earth's strata, and comminute its particles. The specimens of the bottom brought up by the deep-sea soundings made by Lieut. O. H. Berryman, U. S. N., were examined by the late Prof. Bailey, of West Point. His investigations showed that the bottom of the ocean was composed of microscopic crustacea, which he believed to be generated in the localities from which they were raised. They present organic forms of great delicacy and fragility of structure, and it is believed that they could not be produced without either light or heat. We know that none of the former can reach them, and therefore conclude that their generation depends upon the latter. The gases for these organic forms, if required, would, from the enormous pressure, be found in their liquid state.

Although I am convinced that there is no better mode of ascertaining the existence and course of the Oceanic Circulation, than by thermometrical observations on the surface and in the depths of the sea, I feel satisfied that we have, as yet, no reliable instruments for making those observations with precision.

The instruments for recording the temperature of the great depths possess much ingenuity. Saxton's metallic thermometer, in use by the Coast Survey, is, when carefully used, one of the most perfect; but very many of its results are discordant and evidently erroneous. Those obtained by Lieut. O. H. Berryman, when engaged in making the soundings across the Atlantic Ocean for the telegraph, are ex-

tremely discordant, varying, at the same depths and nearly in the same localities, from 30° to 24°, 20°, 15°, 10°, and 5° below the freezing-point. In some instances, the record shows twice the temperature at the same depth. Lieut. Berryman reports having great confidence in Saxton's instruments, and believes that every reliance can be placed in them. He cites instances where two have been used, in taking the deep-sea temperature, giving the same result, within half a degree of each other. From his experiments and those of others, after a careful examination, I think it will be evident, that these instruments are not to be relied on when subjected to great pressure, and are liable to become deranged by any concussion, even that caused by the lead to which they are attached in striking the bottom. On comparing this with Six's glass self-registering thermometer, they have been found to agree, when the depths are less than 300 fathoms. It is to be desired that some reliable test should be made, and the defects obviated by its ingenious inventor, so as to avoid, if possiblc, disturbance by pressure or concussion.

It is hoped that investigations will be directed to the deep-sea temperatures, in which little progress has as yet been made — attention having rather been given to obtain a knowledge of the *actual depth* of the ocean — a result of comparatively little moment. Sufficient has been done to show the direction we should persistently follow, by making a regular series of observations on the temperature at the surface, and at depths of from 100 to 500 fathoms, on parallels 5° apart, and on meridians from 50 to 100 miles asunder. This could be effected at little expense, as our national vessels pass to and from the foreign stations. In the year 1846, the then Secretary of the Navy, at my request, ordered the steamer Missouri, bound for the Mediterranean, to be provided with suitable instruments, to make a series of observations on the surface and deep-sea temperatures in crossing the Atlantic; but they failed to be carried out or to receive any attention, in consequence of the haste to convey our Minister to China, who took passage in that vessel. We trust that other attempts may be more successful, and results obtained.

In reviewing the foregoing remarks on the circulation of the oceans, we cannot fail to be struck with the order, uniformity, and system which everywhere prevails. We perceive, on the one hand, a great body of water flowing onward from right to left, and another, in an opposite hemisphere, equally large and rapid, making its gyration from left to right — deep seas giving out their waters almost continuously, while an indraught is constantly found to set into shallow seas. Notwithstanding these apparent anomalies, which, at first view, appear so

contradictory, they all go to prove the truth of the laws which govern and harmonize the forces we have cited in our explanation of the general circulation. In thus accounting for the many phenomena by these well-known forces, the pressure and movements of fluids according to their established laws, joined with the influence of heat, we are under the belief that they must be considered fully adequate to the end of producing a constant and uninterrupted flow of the waters by which the circulation is established and maintained.